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CLINICAL REVIEW

Upper airway imaging in pediatric obstructive sleep apnea syndrome

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S U M M A R Y

Obstructive sleep apnea syndrome in children is a manifestation of sleep-disordered breathing and associated with a number of complications. Structural narrowing of the upper airway in combination with inadequate compensation for a decrease in neuromuscular tone is an important factor in the pathogenesis. Adenotonsillar hypertrophy is the most important predisposing factor. However, many other causes of craniofacial defects may coexist. Additionally, the pathogenesis of narrowing is more complex in certain subgroups such as children with obesity, craniofacial malformations, Down syndrome or neuromuscular disorders. The diagnosis of obstructive sleep apnea is based on an overnight polysomnography. This investigation is expensive, time consuming and not widely available. In view of the major role of structural narrowing, upper airway imaging could be a useful tool for investigating obstructive sleep apnea and in establishing the site(s) of obstruction. Several radiological techniques (lateral neck radiography, cephalometry, computerized tomography, magnetic resonance imaging and post-processing of these images using computational fluid dynamics) have been used to investigate the role of structural alterations in the pathogenesis. We reviewed the literature to examine if upper airway imaging could replace polysomnography in making the diagnosis and if imaging could predict the effect of treatment with a focus on adenotonsillectomy. There is a limited number of high quality studies of imaging predicting the effect of treatment. To avoid unnecessary risks and ineffective surgeries, it seems crucial to couple the exact individual anatomical risk factor with the most appropriate treatment. We conclude that imaging could be a non-invasive tool that could assist in selection of treatment.

Introduction

Obstructive sleep apnea syndrome (OSAS) is a manifestation of sleep-disordered breathing (SDB) in children [1]. OSAS is characterized by prolonged episodes of increased upper airway (UA) resistance and respiratory effort with partial (obstructive hypopnea) or complete (obstructive apnea) UA obstruction during sleep. The syndrome is often associated with snoring, intermittent hypoxemia, hypercarbia and/or sleep disruption. Additionally, OSAS is associated with a number of significant complications such as daytime neurobehavioral problems, learning deficits, growth retardation and cardiovascular complications [2–5]. Therefore OSAS needs to be treated correctly.

The structural narrowing of the UA in combination with inadequate compensation for a decrease in UA neuromuscular tone is an important factor in the pathogenesis of OSAS [6,7]. Adenotonsillar hypertrophy is the most important predisposing factor for UA narrowing in otherwise healthy children [8]. However, many other causes of craniofacial defects may coexist such as mandibular deficiency, tongue and soft palate enlargement, and inferior displacement of the hyoid bone [9–11]. Additionally, the pathogenesis of UA narrowing is more complex in certain subgroups such as children with obesity, craniofacial malformation, Down syndrome (DS) or neuromuscular disorders. The complexity of the pathogenesis of OSAS in these children is illustrated by a high incidence of residual OSAS after adenotonsillectomy (AT) and by a frequent need for additional treatment. For instance, residual OSAS after AT has been reported in 54–88% of obese children compared to 15–26% of non obese children [12–14]. Lumeng et al. also demonstrated that the prevalence of OSAS in these subgroups

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Abbreviations

2-D/3-D	2-dimensional/3-dimensional
AHI	apnea hypopnea index
AN	adenoidal-nasopharyngeal
AT	adenotonsillectomy
BMI	body-mass index
CAD	computer aided design
CBCT	cone-beam computed tomography
CFD	computational fluid dynamics
CI	confidence interval
CSA	cross-sectional area
CT	computed tomography
DS	Down syndrome
MDCT	multiple detector computed tomography
MRI	magnetic resonance imaging
OAHI	obstructive apnea hypopnea index
OSA	obstructive sleep apnea
OSAS	obstructive sleep apnea syndrome
PSG	polysomnography
RDI	respiratory disturbance index
ROC	receiver operating characteristic
SDB	sleep-disordered breathing
SNA	sella, nasion and A-point
SNB	sella, nasion and B-point
T1	longitudinal relaxation time
T2	transverse relaxation time
TP	tonsillar-pharyngeal
UA	upper airway

Glossary of terms

Apnea hypopnea index:	index of sleep apnea severity that combines apneas and hypopneas. The apneas (pauses in breathing) must last for at least two breathe cycles and are associated with a decrease in blood oxygenation.
Brodsky scoring system:	scoring of the hypertrophy of the tonsils
Mallampati scoring system:	is used to predict the ease of intubation, it assesses the height of the mouth. A high score is associated with a higher incidence of sleep apnea.
Obstructive apnea:	repetitive pauses in breathing during sleep, is usually associated with a reduction in blood oxygen saturation and caused by obstruction of the upper airway.
RDI:	Used in PSG, it reports respiratory events during sleep and includes respiratory-effort related arousals (RERAs). RERAs are arousals from sleep that do not technically meet the definitions of apneas or hypopneas, but do disrupt sleep. They are abrupt transitions from a deeper stage of sleep to a shallower.
SaO_2:	saturation level of oxygen in hemoglobin

was markedly increased compared to the prevalence of 1–4% observed in the general population [15]. Obese children have a prevalence ranging from 13 to 59% [16], and children suffering from DS have a prevalence ranging from 30 to 100% [17–21]. It is also common in children with neuromuscular disorders such as 15.4% in cerebral palsy cases [22] and it is present in 54% of achondroplasia cases [23]. Additionally, children with craniofacial syndromes are often affected with a prevalence of 85% in patients with Pierre-Robin sequence [24] and 8.5% in those with non-syndromic cleft palate [25].

The gold standard for the diagnosis of OSAS is an overnight polysomnography (PSG) [26]. However, it is expensive, time-consuming, labor-intensive and not universally available. Furthermore, PSG does not provide any information regarding the level of UA obstruction or whether there are multiple levels of obstruction [27,28]. In a systematic review, Brietzke et al. demonstrated that the patient's history and physical examination were not sufficiently reliable for the diagnosis of OSAS. [29]. Certel et al. also performed a systematic review on the diagnostic accuracy of clinical symptoms and signs in predicting OSAS. The authors concluded that neither single nor combined symptoms or signs have satisfactory performance in predicting OSAS [30]. Furthermore, several studies have concluded that there is no significant correlation between the subjective assessment of tonsil size and OSAS severity. Howard et al. concluded that only objective tonsil measurements, including the volume and weight of the tonsils after AT, were significantly predictive of OSAS severity [31,32]. Montgomery–Downs et al. investigated the utility of digital photographs for tonsillar grading, as they provide more time to evaluate and make mental calculations. The photograph grading did not differ between physicians, suggesting that this method gave consistent information. However, using photographs for grading often resulted in an underestimation of tonsil size, compared to in-person grading. Additionally, the physicians did not do a comparison with objective tonsils. As such, the clinical relevance of this approach is not clear [33]. A retrospective study investigated the correlation between obesity and severity of OSAS. They included 482 children between the ages of 4 and 9 y (mean age: 6 y), and 111 children were obese. The incidence of AHI in the obese group was significantly higher (odds ratio: 2.03, 95% confidence interval [1.32–3.12]), but there was no significant difference in tonsil size [34]. Another retrospective study compared 206 obese children and 206 non-obese children between the ages of 1–16 y. In contrast to the study by Lam et al., these researchers found a correlation between adenotonsillar size and apnea hypopnea index (AHI) in non obese children ($r = 0.22$, $p < 0.001$), but not in obese children. Tonsilsize was determined by the evaluating physician during visual inspection. The size was scored using a likert scale range, tonsil size was assigned a score of zero (no tonsils present) to four (kissing tonsils). Adenoid size was determined from a blind review of lateral neck radiographs. The adenotonsillar size was smaller in obese children (3.85 ± 0.16 vs. 3.01 ± 0.14) and surprisingly, higher Mallampati scores were observed in obese children. This finding suggests that soft-tissue changes and fat deposition may play a role in the pathogenesis of OSAS in these subjects [35]. In view of the major role of structural narrowing of the UA in the pathogenesis of OSAS in children and the conflicting data mentioned above, UA imaging could be a useful tool in diagnosing OSAS and investigating the site(s) of UA obstruction. Several radiological techniques have been used to

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investigate the role of structural alterations in the pathogenesis of OSAS. These radiological techniques include lateral neck radiographs, cephalometrics, computerized tomography (CT), magnetic resonance imaging (MRI) and post-processing of these images using computational fluid dynamics (CFD). In view of the widespread use of these imaging techniques and the high prevalence of OSAS especially in certain subgroups such as children with obesity or Down syndrome, we reviewed the literature to examine the two following questions.

1) Can UA imaging replace the PSG in making the diagnosis of OSAS?
2) Can it predict the effect of treatment with a focus on adenotonsillectomy?

Methods

A literature search was performed using Pubmed and Cochrane Central register of Controlled Trials. The scope of the research included English-language articles concerning children and adolescents aged 1–17.9 y. We also used relevant references from the articles. All database searches were performed from August 2013 to January 2014. We used the following search terms: children, pediatrics, obstructive sleep apnea, OSAS, sleep-disordered breathing, imaging, CT, MRI, functional imaging, cephalometry and lateral neck radiography. Papers investigating the diagnostic value of certain imaging techniques are rated by the 2011 guidelines of the American Academy of Neurology 2011, see Table 1 [36].

Results

Can UA imaging replace the PSG in making the diagnosis of OSAS?

Structural narrowing of the UA is an important factor in pediatric OSAS. The main reason for UA narrowing in children is adeno- and/or tonsillar hypertrophy. Additionally, in children between 3 and 5 y nasopharyngeal growth occurs less rapidly than that of the surrounding soft tissues resulting in additional narrowing of the airway [37]. Different imaging methods exist to investigate the pharyngeal airway.

Table 1
Studies of imaging techniques in pediatric OSAS.

First author, year	Class*	Cohort: size, age	Diagnostic yield	Endpoints
Shintani 1996 [51]	II	– 140 with OSAS, 54 controls – 1–9 y	Cephalometry	Adenotonsillar hypertrophy was remarkable in OSAS children. Maxillary protrusion was significantly smaller in the OSAS group for older children only. Mandibular protrusion was significantly smaller in the OSAS group at younger ages. The hyoid bone was significantly lower in the OSAS group.
Brooks 1998 [42]	III	- 33 with suspected OSAS (16 in OSAS group, RDI > 5 events/h) – 0.4–11.6 y	Lateral neck radiograph	Lymphoid hyperplasia affects the severity of apnea more than the number of obstructive apneas. A significant relationship was seen between AN ratio and the duration of obstructive apneas.
Kawashima 2000 [60]	III	– 15 with OSAS – 4.7 (range 3–5) y	Cephalometry	The study concluded that: 1) sleep apnea was often associated with mandibular retrognathia, 2) the lower incisors tended to exhibit a retrocline, 3) there were no significant differences in angular and linear measurements in the cranial base, and 4) the apneic children had a narrower epipharyngeal airway space.
Arens 2001 [63]	III	36 in total; 18 with OSAS, 4.8 ± 2.1 y and 18 controls, 4.9 ± 2.0 y	MRI	In children with moderate OSAS, the upper airway is restricted both by the adenoid and tonsils; however, the soft palate is also larger in this group, adding further restriction.
Li 2002 [11]	III	– 35 with OSAS (11 AHI<10, 24 > 10 events/h) - 6.2 (range 4–10.3) y	Lateral neck radiograph	Tonsillar hypertrophy correlates positively with the severity of OSAS. TP ratio has high sensitivity and specificity in predicting moderate/severe OSAS.
Jain 2002 [28]	III	– 40 total; 30 with OSAS symptoms, 10 with inflammatory symptoms (22 OSAS (AHI>5 events/h)) – 4–12 y	Lateral neck radiograph	All patients with a relative adenoid size ratio greater than 0.64 were found to have OSAS. No correlation between tonsil size and grade of OSAS.
Fregosi 2003 [62]	III	– 18 awake children with OSAS – 7–12 y	MRI	They concluded that 7- to 12-y-old children with a narrow retropalatal air space have significantly more apneas and hypopneas during sleep compared with children with relatively unobstructed retropalatal airways.
Donnelly 2003 [66]	III	– 32 in total; 16 with OSAS, 16 controls – 6 (range 10 d–19) y	Cine MRI	Results showed that there were significant differences in the patterns of dynamic airway motion between young patients with and those without OSA.
Abbott 2004 [67]	III	– 52 in total; 31 with OSAS and 21 controls - OSAS; mean age 11.3 y, controls; mean age 3.5 y	Cine MRI	Transverse MR imaging demonstrates both airway distention and collapse in children with OSAS.
Cozza 2004 [59]	III	40 in total; 20 with OSAS, 5.91 (range 4–8) y and 20 controls, 6 (range 5–7) y.	Cephalometry	The study showed that a number of statistically significant differences were detected in craniofacial morphology.
Ozdemir 2004 [54]	III	- 39 with OSAS – 7.5 (range 4–12) y	Cephalometry	Cephalometric data and AHI score severity were significantly correlated. Adenotonsillar hypertrophy affects the cephalometric measurements adversely.
Donnelly 2004 [97]	III	– 27 children with DS and OSAS - mean age 9.9 y	Cine MRI	The study concluded that persistent OSAS in children with Down syndrome who have undergone previous adenoidectomy and tonsillectomy has multiple causes.
Arens 2005 [64]	III	20 in total; 10 with OSAS, 10 controls – 4.3 (range 2–7.2) y	MRI	The study concluded that fluctuations in airway area during tidal breathing are significantly greater in subjects with OSAS compared with control subjects.

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Table 1 (*continued*)

First author, year	Class*	Cohort: size, age	Diagnostic yield	Endpoints
Xu 2006 [43]	III	– 50 in total: 31 with OSAS, 19 with primary snoring - OSAS group: 7.8 ± 3.2 y Primary snoring: 8.1 ± 3.7 y	Lateral neck radiography	The combination of clinical and radiologic findings might be helpful to screen for children with clinically significant OSAS.
Fricke 2006 [44]	III	– 89 in total; 52 with persistent OSAS, 9.71 ± 5.63 y and 37 controls, 5.62 ± 3.77 y	MRI	Lingual tonsil enlargement is relatively common in children with persistent OSAS after surgery, especially in patients with DS.
Arens 2011 [61]	III	44 in total; 22 with OSAS and obesity, 12.5 ± 2.8 y, 22 controls with obesity, 12.3 ± 2.9 y	MRI	The study concluded that: 1) UA lymphoid hypertrophy is significant in obese children with OSAS. 2) No association between parapharyngeal fat pads and OSAS severity .
Persak 2011 [84]	III	Six in total; three with OSAS, 5.2 (range 2.4–7.7) y and three controls, 4.7 (range 2.9–6.13) y	Volume-gated dynamic MRI and CFD	The study concluded that upper airways of subjects with OSAS were generally much more compliant during tidal breathing.
Pirilä-Parkkinen 2011 [50]	III	– 36 with OSAS - 7.3 (range 4.8–9.8) y	Cephalometry and MRI	This study concluded that the 2-D lateral cephalogram is a valid method in recognizing pharyngeal obstruction.
Nandalike 2013 [95]	III	– 27 obese children with OSAS - age 13.0 ± 2.3 y	MRI	The study concluded that the UA in obese children with OSAS after adenotonsillectomy showed significant residual adenoid tissue and an increase in the volume of the tongue and soft palate**.
Cappabianca 2013 [65]	III	-80 in total; 40 with OSAS, 40 controls - 8.9 (range 4–14) y	MRI	Results showed that not only adeno-tonsillar hypertrophy is important in determining the clinical syndrome: soft palate enlargement and certain skeletal patterns can even assume greater importance in the genesis and in the progression of the obstruction. MRI proved to be an accurate technique in the evaluation of the prevalent risk factor in children affected by OSAS, leading to the most appropriate surgical approach.
Van Holsbeke 2013 [71]	III	- 23 with OSAS, 10 controls - 6 (range 2.8–9.2) y	Functional respiratory imaging, CFD endpoints on CT	Functional imaging parameters are highly correlated with OSAS severity and are a more powerful correlate than clinical scores of UA patency.
Wootton 2014 [83]	III	30 in total: 15 with OSAS, 13.2 ± 2.1 y and 15 controls, 13.1 ± 2.1 y	Functional respiratory imaging, CFD endpoints on MRI	CFD model endpoints based on pressure drops in the pharynx were more closely associated with the presence and severity of OSAS.

2-D: two-dimensional; AN: adenoidal-nasopharyngeal; AHI: apnea hypopnea index; CFD: computational fluid dynamics
* Class:
Class II
- Cohort study with retrospective data collection or case-control study. Study meets a. Inclusion criteria defined and b. At least 80% of enrolled subjects have both the diagnostic test and disease status measured
- Includes a broad spectrum of persons with and without the disease
- The diagnostic test result and disease status are determined objectively or without knowledge of one another
Class III
- Cohort or case control study
- Narrow spectrum of persons with or without the disease
- The diagnostic test result and disease status are determined objectively, without knowledge of the other or by different investigators
CT: computed tomography; DS: Down syndrome; MR: magnetic resonance; MRI: magnetic resonance imaging; OSA: obstructive sleep apnea; OSAS: obstructive sleep apnea syndrome; RDI: respiratory disturbance index; TP: tonsillar-pharyngeal; UA: upper airway; Y: year
** This was the only study that showed a succesrate of the AT. Resolution of OSAS was noted in 44% (12 of 27) but only in 22% (4 of 18) of those with severe OSAS (AHI >10 events/hour).
Rated according to American Academy of Neurology 2011. Clinical practice guideline process manual [36].

These imaging methods will be discussed separately with regards to their value in the diagnosis of OSAS.

Lateral neck radiography

A lateral neck X-ray is a plain X ray of the neck from the side using a small amount of radiation with an average of 0.2 millisievert (mSv) (reported variation in the literature ranges between 0.07 and 0.3 mSv) [38]. The obtained image shows the following structures: the vertebrae, the oral and nasal airways, the nasopharynx, part of the trachea, the epiglottis, the soft tissue in front of the vertebrae and the adenoids and tonsils. Adenoid/tonsil size can be determined using different measures and ratios including adenoid thickness [39], airway-soft palate ratio [40], adenoidal-nasopharyngeal (AN) ratio [41] and other ratios as presented in Fig. 1. Lateral neck radiography is relatively simple, widely accessible and has a low cost. However, the images are taken in an upright position in awake patients. Furthermore, the airway is depicted in a two-dimensional (2-D) view, resulting in a possible loss of information.

Brooks et al. evaluated 33 children with a mean age of 4.5 y by lateral X-ray and PSG. Children with obvious neurologic or craniofacial abnormalities were excluded. The AN ratio (according to the method described by Fujioka) was only correlated with the duration of obstructive apneas ($r = 0.55$; $p < 0.01$), and no correlation was found with tonsil size. Obesity was the only marker related to the apnea hypopnea index in regression analysis. However, children with OSAS had a larger AN ratio (0.83 ± 0.3 vs. 0.69 ± 0.03; $p = 0.003$), resulting in reasonable positive and negative predictive values of 71% and 75%, respectively [42]. Jain et al. evaluated with lateral neck X-ray 40 children, ranging from 4 to 12 y who had adeno- and/or tonsil hypertrophy. Children with DS, craniofacial anomalies, delayed developmental milestones, mental retardation and/or excessive obesity were not included. This study also showed a significant correlation between adenoid size and the degree of OSAS. No correlation was found between tonsillar hypertrophy and OSAS. All patients with a relative adenoidal hypertrophy (CD ratio, Figure 1) (See Fig. 1) greater than 0.64 were found to have OSAS (criterion was AHI > 5 events/h) [28]. Li et al. performed lateral neck radiography in 35 children ranging in age from 4 to 10 y with a mean age of 6.2 y with suspected OSAS and measured the tonsillar-pharyngeal (TP) ratio as a measure of

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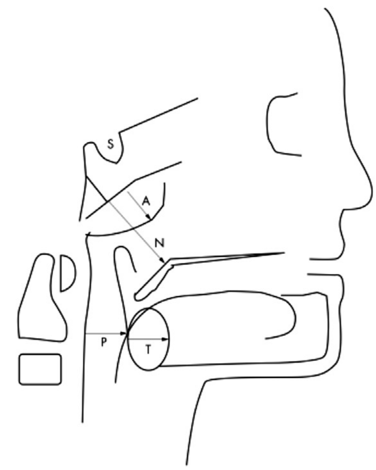
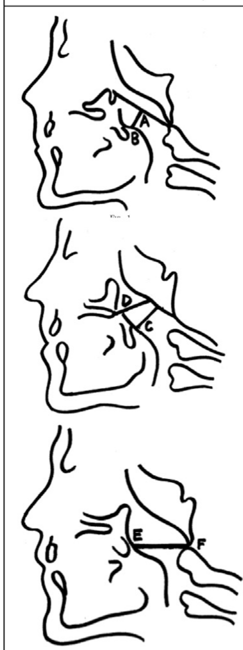
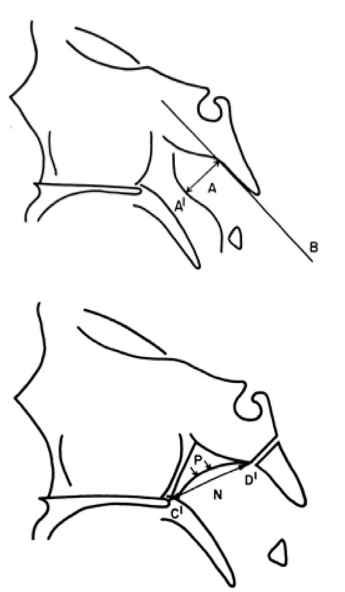
	A: adenoid; N: nasopharyngeal measurement; P: pharyngeal measurement; S: sella turcica; T: tonsil. A and T are measured as a perpendicular distance at their maximum convexity. T/P is the ratio of the width of the tonsil to the depth of the pharyngeal space. [11]
	AB – (measured in mm). Absolute value of adenoidal hypertrophy expressed as a perpendicular distance at maximum convexity – measured from a line joining the uppermost part of the pterygomaxillary fossa and anterior tip of atlas. CD ratio – Represents relative value of adenoidal hypertrophy, where C is the distance from the point of maximum thickness of adenoids along a line perpendicular to the line that is drawn along the straight part of the basiocciput and D is the distance from the posterior nasal spine to the antero-inferior edge of the sphenobasioccipital synchondrosis. EF – (measured in mm). Distance from posterior nasal spine to the surface of the adenoid shadow along the line drawn from the posterior nasal spine (E) to the basion (F). [28]
	Adenoidal-nasopharyngeal ratio: A: distance A' point of maximal convexity along inferior margin of adenoid shadow to line B, drawn along straight part of anterior margin of basiocciput. N: distance C' posterior superior edge of hard palate to D', anterioinferior edge of phenobasioccipital synchondrosis. [41]

Fig. 1. Ratios and measurements derived from lateral neck radiographyReprinted with permission of the BMJ journals, Journal of laryngology & otology and the American journal of roentgenology. Copyright © 2014 [11,28,41].

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tonsillar enlargement (Fig. 1). An important comment about this study is that nearly all children included had tonsillar hypertrophy. Children with obesity or growth failure were not included. There was a significant correlation between the TP ratio and the AHI ($r = 0.8$; $p < 0.001$) and oxygen desaturation index ($r = 0.51$; $p = 0.002$). Surprisingly, no correlation was found between tonsil size and the TP ratio. The receiver operating characteristic (ROC) curve analysis revealed that a TP ratio cut off of 0.5 was optimal for predicting moderate-to-severe OSAS (AHI > 10 events/hour), with the area under the curve being 1.0. The corresponding sensitivity and specificity were 95.8% and 81.8% respectively, while the positive and negative predictive values were 92.0% and 90.0% respectively [11]. Xu et al. reviewed data of 50 children ranging in age from 4 to 18 y with a mean age of 7.8 ± 3.2 y in the OSAS group ($n = 31$) and 8.1 ± 3.7 y in the primary snoring group ($n = 19$). They all underwent a clinical assessment, lateral neck radiograph and PSG. The aim of this study was to determine whether parents' observation, clinical examination and lateral upper airway radiograph were useful in diagnosing OSAS. Children with a history of chronic pulmonary and neuromuscular diseases were excluded. They used the AN ratio with cut-off values of <0.5 for normal or mild and >0.5 for moderately or severely enlarged adenoids. In total, 81% of subjects with OSAS had UA narrowing on X-ray (sensitivity 81% and specificity 58%). Second, this study demonstrated that the addition of other predictors of OSAS could make this sensitivity higher. Combining UA narrowing with mouth breathing or nocturnal enuresis increased the sensitivity to 90%, although the specificity remained at 58%. The combination of observed apnea during sleep, nocturnal enuresis, intrusive naps, mouth breathing, enlarged tonsils and radiologic features of narrowing had a sensitivity of 94% but a specificity of only 42%. The combination of all these predictors had a positive predictive value of 73% and a negative predictive value of 80% [43].

In contrast to the general population, lingual tonsil hypertrophy in OSA is believed to be more prevalent in children with DS [44]. A retrospective review quantified lingual tonsil size in 105 DS children (mean age 5.2 y) and 89 controls (mean age 5.4 y) by c-spine radiographs. Lingual tonsil size was larger in the DS group (2.1 mm vs. 0.8 mm) . They concluded that c-spine radiographs are useful in identifying lingual tonsil hypertrophy. However, further studies are needed to confirm this finding [45].

Cephalometry

Cephalometry is a useful technique for evaluating anatomical abnormalities in patients with OSAS [46–48]. It involves a standardized lateral radiographic view of the head and neck. Cephalometry, like a lateral neck X-ray, is relatively simple, widely accessible, has a low cost and requires minimal radiation. In cephalometry, the position of the head is very important and therefore, using a fluid level can aid in the evaluation of the correct position. This method shows skeletal (including mandibular and hyoid position) and soft-tissue (tongue and soft palate) UA structures. Several markers, distances and ratios can be calculated with this imaging technique (Fig. 2).

There are several limiting factors of cephalometry. One limiting factor, which also occurs with lateral neck radiographs, is that the assessment of UA structure is conducted in the upright position in awake patients. One study in adults investigated the difference between supine and upright lateral cephalograms and observed no additional differences [49]. There are currently no such studies available in children. Another confounding factor of cephalometry, which also occurs in lateral neck X-rays, is that these methods are limited by low soft tissue resolution. As such, both techniques utilize only lateral view images and 2-D images. Pirilä-Parkkinen et al. investigated whether the capability of 2-D lateral cephalography in recognizing pharyngeal obstruction compared to 3-D MRI and clinical observation. This study investigated 36 prepubertal children with OSAS. The study showed an association between the cephalometric nasopharyngeal and retropalatal airway measurements and MRI findings in children with SDB. These findings suggest that a lateral cephalography radiograph is a useful screening tool when evaluating nasopharyngeal or retropalatal airway size. However, the authors also concluded that cephalography should not be used as a diagnostic tool because retroglossal pharyngeal measurements did not correlate with MRI variables. Palatal tonsils mainly are situated in the retroglossal region and because of their lateral position, enlarged tonsils can cause the transversal narrowing of the retroglossal airway, which is not detectable on the anteroposterior view of the cephalogram [50].

Although adenotonsillar hypertrophy is the most common cause of OSAS, the influence of skeletal abnormality should also be considered as a cause of UA narrowing. Shintani et al. investigated 194 children ranging in age from 1 to 9 y with a mean age of 4.5 ± 1.7 y in the OSAS group ($n = 140$) and a mean age of 4.7 ± 2.5 y in the control group without habitual snoring and apnea ($n = 54$). Cephalometric analysis was performed and they concluded that adenotonsillar hypertrophy was highly prevalent in the OSAS group at all ages. The maxillary protrusion expressed by the sella, nasion and A-point (SNA) angle was significantly smaller in the OSAS group for children between 5 and 9 y old and the mandibular protrusion expressed by the sella, nasion and B-point (SNB) angle was significantly smaller in the OSAS group for children between 1 and 2 y old. The GoGnH angle and MP-H distance of the hyoid bone were significantly lower in the OSAS group for children between 3 and 6 y of age, suggesting that craniofacial structure could play a role in OSAS [51,52]. Several studies have investigated whether cephalometry could predict the diagnosis of OSAS. A recent systematic review investigated the association between craniofacial and UA morphology in pediatric SDB. None of the studies provided strong evidence, while two of four studies of children with OSAS were rated moderately strong for the level of evidence. This review concluded that children with OSAS have an increased ANB angle (difference between SNA and SNB) of 1.64° [0.88; 2.41 95% Confidence interval (CI)] ($P < 0.0001$) compared to the controls. This increase is due to a reduced anteroposterior width of the UA at the level of the posterior nasal spine and superiorly at the level of the adenoidal mass. However, it is unclear if this slightly difference of less than 2° is clinically relevant. There was strong evidence that children with OSAS had a reduced UA sagittal width, as shown by reduction in PNS-AD1 distance by 4.17 mm ($P < 0.0001$) and a reduction in PNS-AD2 3.12 mm ($P < 0.0001$) compared to the controls. Although differences in bony structures were revealed by this meta-analysis, the clinical relevance of these findings remains unclear and the authors suggested that more trials with 3-D imaging are necessary [53]. Ozdemir et al. investigated the correlation between cephalometry and AHI in 39 children. There was a clear correlation between a number of cephalometric indices and AHI. Furthermore, adenotonsillar hypertrophy adversely affected the cephalometric measurements and possibly increased the risk for persistent or future OSAS. The authors therefore concluded that their study stressed the need for early and effective therapy for adenotonsillar hypertrophy in children with OSAS [54]. Several studies have also described the relationship between cephalometry and the long-term risk of anatomical divergence. Case series and several trials have suggested that children with mouth breathing, adenotonsillar hypertrophy, or SDB have increased lower anterior face height, increased mandibular plane angle, retropositioned mandible and smaller airway space [54–58]. Guilleminault et al. suggested that maintaining nasal breathing during childhood is important for

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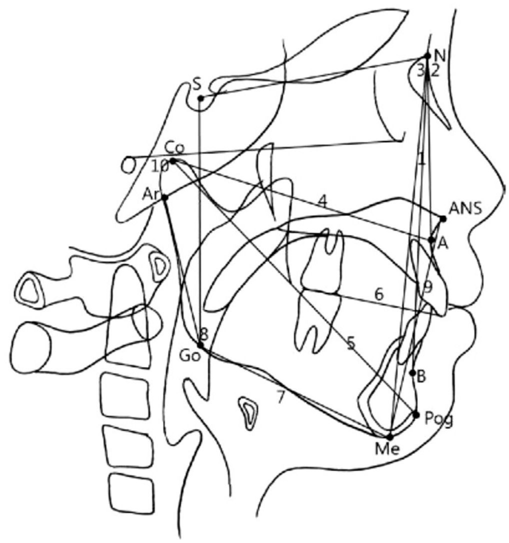

Diagrammatic representation of anatomic points and lines used to identify craniofacial variables.
1, ANB;
2, SNA;
3, SNB;
4, MxUL;
5, MnUL;
6, FH–OP;
7, MPA;
8, gonial angle;
9, LFH;
10, ramal inclination;
11, PFH/AFH.
ANB, point A-nasion- point B; SNA, sella-nasion-point A; SNB, sella-nasion-point B; MxUL, maxillary unit length; MnUL, mandibular unit length; FH, Frankfort horizontal plane; OP, occlusal plane; MPA, mandibular plane angle; LFH, lower facial height; PFH, posterior facial height; AFH, anterior facial height.

Definitions of cephalometric landmarks

S	Sella: midpoint of the fossa hypophysealis
N	Nasion: anterior point at the frontonasal suture
ANS	Anterior nasal spine: most anterior point of the nasal spine
A	Deepest anterior point in the concavity of the anterior maxilla
Ar	Posterior ramus plane: the intersection of a line along the posterior border of the mandible and the inferior border of the basilar occipital bone
B	Deepest anterior point in the concavity of the anterior mandible
Go	Gonion: a mid-plane point at the gonial angle located by bisecting the posterior and inferior borders of the mandible
Me	Most inferior point of bony chin
Pog	Most anterior point of bony chin

Definitions of cephalometric angles

SNA	Angle from sella to the nasion to the subspinal point
SNB	Angle from sella to the nasion to the supramental point
ANB	Angle from the subspinal point to the nasion to the supramental point

Fig. 2. Cephalometric anatomic points. Reprinted with permission of the journal of oral and Maxillofacial Surgery. Copyright © 2014. [48].

preventing alterations of the craniofacial morphologic characteristics [58]. Cozza et al. showed significant reduced mandibular intermolar width in these children and Kawashima et al. suggested that mouth breathing and OSAS induce morphological maxillomandibular changes (long face syndrome). However, the review could not provide evidence to support a direct relationship between craniofacial structure and pediatric SDB [53,54,59,60].

Magnetic resonance imaging (MRI)

It is possible to evaluate the UA in a cross-sectional (imaging in the axial, sagittal and coronal planes) way, with moving images during sleep by cine MRI or in 3-D reconstruction (Fig. 3). An important advantage of MRI is that in contrast to CT, MRI does not require ionizing radiation. However, MRI is expensive, and requires a long examination time, resulting in a higher probability of motion artifacts, which often results in the requirement for a long examination and sedation. The use of sedatives makes the procedure more invasive, does not completely mimic normal sleep and affect UA dimension in an unpredictable way. Children with OSAS have a decreased UA muscular tone and the patients tend to have noisy breathing and oxygen desaturation. This phenomenon is uncommon in children without OSAS and the UA muscular tone is not completely the same in sedated patients. MRI is also possible without sedation, but because of the long examination time the chance of artifacts due to swallowing and movements are increased. In contrast to PSG, it is not possible to document sleep stages in MRI because the strong magnetic field prevents the use of electrodes during imaging.

Several studies have investigated the relationship between UA anatomy assessed by MRI and OSAS severity. A limitation of the majority of these studies was the decision to exclude patients with predisposing factors for OSAS such as obesity. As such, they identified differences in the anatomy of children with and without OSAS, but could not conclude whether MRI could make the diagnosis of OSAS. The following structural differences have been described. Recently, Arens et al. investigated the body fat composition and UA structure in 44 obese children, 22 with OSAS and 20 controls. They concluded that UA lymphoid hypertrophy, parapharyngeal fat pads and abdominal visceral fat were significantly increased in obese children with OSAS. However, only lymphoid tissue, but not parapharyngeal fat pads and abdominal visceral fat, correlated with the severity of OSAS in regression analysis [61]. Another study investigated whether there was a correlation between the pharyngeal size and soft tissue anatomy and the severity of SBD in children including obese children. Eighteen awake children underwent MRI. AHI correlated with the size of the tonsils and soft palate and inversely with the volume of the

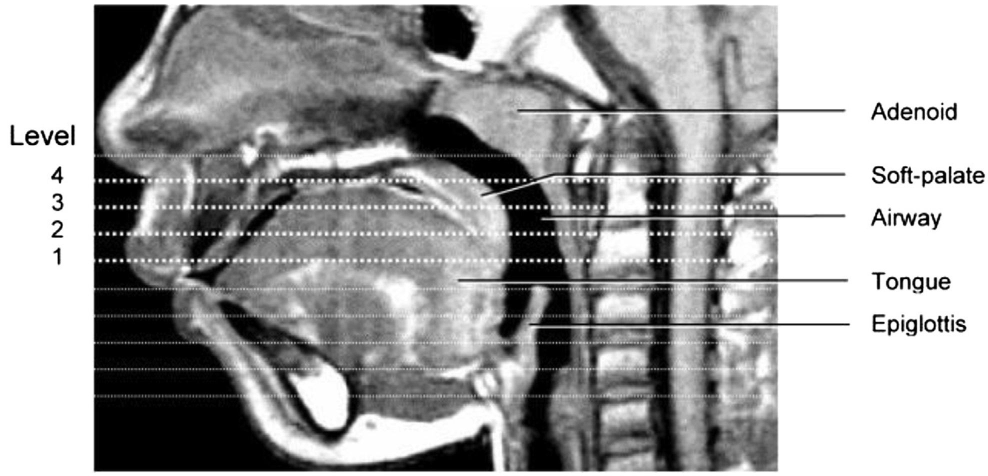

Fig. 3. UA imaging by MRI. Reprinted with permission of the American Thoracic Society. Copyright © 2014 American Thoracic Society [64].

oropharynx. The narrowest point in the pharyngeal airway was smaller in the children with more severe OSAS and this point was in the retropalatal airway in almost all subjects. This study was the first to show that children with more severe OSAS had a narrower airway, particularly in the retropalatal region where the soft palate, adenoids, and tonsils overlap. These results indicated that almost 75% of the variance in AHI could be explained by the tonsil cross-sectional area (CSA) and soft palate. There was no correlation between BMI percentile and OSAS severity [62]. Arens et al. extensively studied the UA in sedated children with OSAS by MRI. In a first study, they compared the UA structure in 18 young children with OSAS (mean age 4.8 y) and 18 controls (mean age 4.9 y). They showed a correlation between increased tonsil and adenoid volume and AHI in sedated children [63]. Another study investigated 10 children with adenotonsillar hypertrophy and OSAS (mean age of 4.3 y) and 10 controls (mean age 5 y). Children with OSAS had a smaller UA volume, particularly during inspiration, whereas dilation occurred during expiration. The OSAS group had larger adenoid and tonsils in comparison with the control group. The volumes of mandible and tongue were similar in both groups. The study concluded that the UA is restricted by the adenoid and tonsils in children with moderate OSAS. Additionally, the study found that further UA restriction in OSAS patients could be caused by enlargement of the soft palate [64]. Cappabianca et al. investigated 40 children, 20 with OSAS and 20 controls, with a mean age of 8 y. Obese children, children affected with a syndrome, or children with craniofacial skull abnormalities were excluded. All of the children underwent MRI in supine position, without sedation. Longitudinal relaxation time (T1)-weighted axial (to highlight air spaces), sagittal spin-echo images and transverse relaxation time and (T2)-weighted (to highlight pharyngeal soft tissues) sagittal turbo spin-echo images were obtained. Volumetric measurements were made from the T1-weighted images and T2-weighted images and were used to evaluate the lymphoid tissues. This study showed a significantly smaller UA volume (1.4 ± 0.7 cm^3 versus 1.6 ± 0.7 cm^3; $p < 0.001$) and midsagittal nasopharyngeal airway (0.7 ± 0.2 cm^3 versus 1.2 ± 0.4 cm^3; $p < 0.01$) in OSAS patients. The axial cross-sectional area of the oropharyngeal airway was also smaller (0.5 ± 0.3 cm^3 versus 0.8 ± 0.5 cm^3). Children with OSAS also had a significantly lager soft palate volume and midsagittal palate volume. Additionally, the adenoids and tonsils were considerably larger in the OSAS group. With regards to skeletal structure, the study showed that the OSAS group had a smaller mandibular volume and a lower vertical position of the hyoid bone [65].

Cine MRI is also frequently used because OSAS is a dynamic process. Inspiratory airway narrowing during tidal breathing has been observed in children with OSAS. Donnelly et al. investigated 16 young patients with OSAS and 16 without airway problems or airway diseases. These researchers showed several differences concerning dynamic airway motion [66]. OSAS patients were much more likely to demonstrate intermittent collapses of the nasopharynx and exclusively demonstrated intermittent collapse of the hypopharynx. The mean change in diameter of the nasopharynx and hypopharynx, implicating a more compliant UA, was also significantly greater in the OSAS group. Abbott et al. investigated 31 children (mean age of 11.3 y) with OSAS and 21 control children (mean age of 3.5 y). They included OSAS subjects with the following predispositions to obstruction: craniofacial anomalies, DS, persistent OSAS and preoperative evaluation to complex airway surgery. All children underwent transverse phase gradient-echo cine MRI imaging of the hypopharynx with sedation. The airway volumes were obtained by a k-means clustering algorithm and the airway wall motion was described. The study showed airway distention and airway collapse in children with OSAS. Airway volume oscillated in both groups, but the amplitude was much larger in the OSAS group. A clear limitation of this study is the fact that the mean age of the control group was much higher than the mean age of the OSAS patients. A concern about the large difference in age is that UA size may increase by age. In this study however, airway volume did not correlate significantly with age in either the control group or the children with OSAS [67].

Computerized tomography (CT). CT scanning is a fast, non-invasive technique and is available in the majority of institutions. CT images can be taken during wakefulness and sleep. However, a disadvantage of CT is radiation. The radiation dose for a neck CT is approximately 3 mSv for adults [38,68]. The use of adult protocols in children increases the exposure of the children to radiation. Recently, cine CT or ultra-fast CT has been used more frequently and can obtain multiple images with a lower radiation dose. Mulkens et al. compared standard radiography and a low-dose CT scans in the evaluation of the sinuses. The dose of a standard radiography was 0.0528 mSv and 0.096 mSv in the first phase of low-dose MDCT. With a second phase of higher pitch and faster scan rotation the dose could be further lowered to 0.0531 mSv [69]. The radiation from a low-dose CT scan to the neck is around the 1–2 mSv, and depends on the body of the child [70].

Van Holsbeke et al. investigated whether anatomical and functional properties of the airway were correlated with OSAS severity. In that study, 33 children of a mean of 6 y were included of whom 23 children were diagnosed with OSAS. The study concluded that

children with OSAS had a lower volume of UA segment 3, which corresponds to the region between choanae and uvula including the overlap region, and a lower mean cross-sectional area of the UA. These researchers also found a high correlation between OSAS severity and imaging parameters. No correlation was found between the clinical scores of UA patency (Brodsky and Mallampati scoring system) and OSAS severity indicating that imaging might be more powerful in the assessment of UA patency [71].

For completeness, we also included a paper by Ronen et al. They investigated the length of the UA of pre- and postpubertal children by CT. They included 69 boys and girls (4–10 y old prepubertal and 14–19 y old postpubertal) and airway length and normalized airway length/body weight were compared. The airway length of prepubertal children was similar. When normalized to body height, airway length/body height was significantly larger in prepubertal girls. After puberty, airway length normalized for body height was significantly greater in boys. This finding suggests the importance of anatomic changes at puberty in a gender-specific manner [72] and could help to explain why the prevelance of men with OSAS is higher [73].

Cone beam CT. Another 3-D imaging modality is cone beam CT (CBCT). It has been used for many maxillofacial applications such as for implant site imaging and treatment planning for craniofacial surgery and orthodontics [74]. The radiation dose is lower than that of normal CT and is more similar to that of low dose protocol CT. When used in maxillofacial imaging, CBCT produces an eight- to 10-fold lower effective dose than a conventional CT examination using standard protocols. In comparison of the low dose protocol CT, the effective dose may be reduced with an increase of image noise [75–78]. Yamashina et al. evaluated the reliability of CBCT values of the UA air spaces of a phantom compared with those of multidetector row CT. They concluded that the measurement of air spaces with CBCT was quite accurate when multidetector row CT was used [79]. In contrast to studies on adults, there are no studies in the literature regarding the use of CBCT in children with OSAS. Enciso et al. compared the combination of CBCT scan measurements between 10 adults with OSAS and 10 adults who were snorers without OSAS. They found a significant correlation between BMI and the minimum cross-section area in OSAS cases but not in snorers. There was also no correlation between BMI and lateral dimension. They concluded that the combination of CBCT measurements and the Berlin questionnaire could be used as a tool to assess the presence and severity of OSAS [80]. Another review of the use of CBCT in adult patients with OSAS concluded that there is a need for more research, but that the use of CBCT for both preoperative planning and for postoperative evaluation of therapeutic interventions is likely to become increasingly important Thereby, if there are craniofacial and/or orthodontic anomalies, a referral to an orthodontist will be required. [81].

Functional imaging

Functional imaging is a relatively new method for further studying UA physical characteristics, including velocity, turbulence, pressure, wall sheer stress and resistances. This is possible by converting images obtained from MRI, CT scans or CBCT to computerized 3-D models (Fig. 4). These models make it possible to visualize the UA and to calculate specific characteristics using computational fluid dynamics (CFD). CFD allows for the description of regional flow and pressure profiles in and around structures including anatomical structures. CFD numerically solves the Navier–Stokes equations that describe the flow behavior. These equations are solved within a 2-D or 3-D domain, which represents the physical boundaries of the anatomical structure of interest. These 3-D models are then converted to computer aided design (CAD) models that are subdivided into a large number of discrete elements. Every cell is used to calculate the local flow properties such as velocity, pressure, and density. The presence of more elements, and hence, a finer grid, leads to a more accurate flow solution but at the same time increases the computational cost for the simulation. A good knowledge of basic flow behavior is essential for constructing adequate grids. This makes it possible to increase the number of cells in high gradient regions where high solution resolution is necessary. A typical computational grid of the upper airway regions consists of 500,000–1,600,000 cells. Once the computational grid has been constructed it is necessary to determine the flow characteristics including turbulence models and boundary conditions. The boundary conditions are needed to close the large system of equations resulting from solving the Navier–-Stokes equations in each discrete cell. The boundary conditions should be described at the inlet and outlet surfaces. The boundary conditions in the UA models typically consist of the definition of pressure or velocity at the inlet and the outlet of the model. Some studies used data obtained in vivo to define the inlet pressures while other studies have used typical flow rates for inspiration [82].

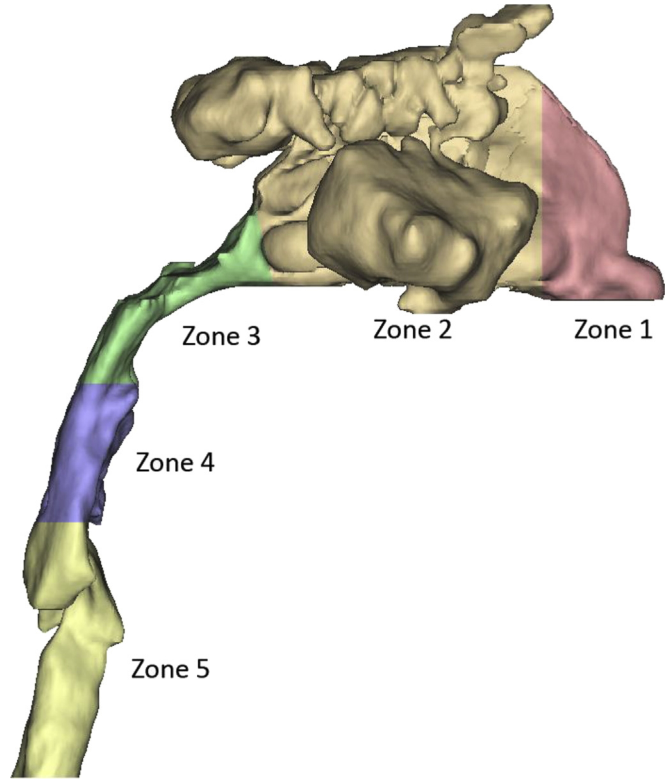

Fig. 4. Computerized 3-D model of the UA. Nostril to bottom of inferior turbinate (zone 1), bottom of inferior turbinate to choanae (zone 2), choanae to tip of uvula (zone 3), uvula to epiglottis (zone 4) and epiglottis to the first thoracic vertebra (zone 5).

Wootton et al. used CFD on MRI images in 15 obese children with OSAS and controls to investigate the correlation between various CFD endpoints, anatomical endpoints and OSAS severity. The subjects were awake with their mouths closed during imaging. CFD measurements based on the magnitude of the pressure change between the entrance to the pharynx and the point of maximum airway restriction in the overlap region were best related to OSAS severity. Both the pressure drop and pressure-drop to flow ratio were on average more than 3.3 times higher in subjects with OSAS. The pharyngeal flow resistance and pressure drop, which included additional pressure losses, especially around the epiglottis and larynx in these models, were also larger in OSAS. There was also a correlation of AHI and the UA flow variables. This study therefore

supports the usefulness of CFD in characterizing the anatomical restriction of the pharynx, and it can be used as an additional tool to evaluate subjects with OSAS [83]. Persak et al. investigated volume-gated dynamic MRI and CFD analysis in three children with OSAS and three controls. These results showed that the UA of children with OSAS was generally more compliant during tidal breathing. The main indication of this method is to investigate physiological changes during obstruction rather than OSAS severity [84]. The study by Holsbeke et al. showed a strong correlation between the CFD derived UA resistance and OSAS severity. The highest correlation coefficient was found with obstructive AHI, respiratory disturbance index (RDI), oxygen desaturation index and SaO_2 [71]. There have been no studies of CFD and CBCT in patients with OSAS, but Van Holsbeke et al. showed the usefulness of CBCT and CFD parameters in the UA [85].

Summary and conclusions

In spite of the availability and widespread use of the imaging techniques discussed in this review, the usefulness of the methods as a diagnostic tool for pediatric OSAS remains understudied. Most studies have investigated the correlation with OSAS severity, although some studies have suggested their possible use as a diagnostic tool. Lateral neck X-ray is a simple technique and has relatively good predictive values for the diagnosis of OSAS. Furthermore, the predictive value can be improved by incorporating certain clinical predictors such as obesity, mouth breathing, nocturnal enuresis, observed apnea during sleep, intrusive naps and enlarged tonsils on clinical examination. In view of the advantages associated with this technique, further studies in other and larger populations are warranted. Like lateral neck radiographs, cephalometric evaluation also utilizes different measures and ratios. It remains unclear if cephalometry can be a diagnostic tool because the published studies have not reported sensitivities or specificities. However, there are clear correlations with OSAS severity. In contrast to lateral radiography and cephalometry, CT and MRI give better insight into UA anatomy because of the assessment in axial, sagittal and coronal planes. MRI provides a detailed assessment of the UA as the pharyngeal size and soft tissue anatomy (including adipose tissue) can all be examined. CT, as well as CBCT, also provides a detailed analysis of the anatomy. Unfortunately, CBCT is not available in all hospitals. Several studies involving MRI or CT have showed detailed correlations with OSAS severity or the identification of critical anatomical sites. However, no data on the sensitivity or specificity of these techniques have been published. Finally, CFD gives additional information on the functional and anatomical properties of the UA such as resistances and flow characteristics, which are based on MRI or CT images. A limited number of studies have used this technique, but there is a correlation with CFD parameters and OSAS severity. This technique can certainly give us more insight in the pathophysiology of OSAS in a non-invasive manner. However, its value as a diagnostic tool needs more study.

In conclusion, there are limited data on the usefulness of the different imaging techniques as a diagnostic tool in pediatric OSAS. Most of the studies had small sample sizes with different inclusion and exclusion criteria. Furthermore, a number of studies excluded patients with predisposing factors for OSAS such as obesity. Conclusions of the different studies suggest that imaging could be a useful tool in diagnosing OSAS. These simple techniques can already assist in predicting the severity of OSAS. Therefore, there certainly is a rationale for further studies on this subject. Finally, a head to head comparison of the different imaging methods, including cost-effectiveness analysis, is warranted.

Can imaging predict the effect of adenotonsillectomy in OSAS?

AT is the first-line treatment in children with OSAS. A meta-analysis including 1079 children showed a normalization of the AHI (defined as AHI < 1 events/hour) in approximately 60% of patients. The population included obese children (15%), while children with craniofacial anatomical defects and neuromuscular diseases were excluded. AHI normalized in 74% of the nonobese children, in contrast to only 39% of obese children [86]. Another meta-analysis that included 578 children (50% obese children; children with craniofacial anatomical defects and neuromuscular diseases were excluded) showed a reduction of AHI in 90%. Only 27% of the children had AHI <1 events/h after AT and 78% had AHI <5 events/h. Children who were older (>7 y), were obese or had more severe OSAS at baseline (AHI > 5) were more likely to have residual disease after AT [12]. A randomized trial investigated whether early-AT results in a better outcome compared with watchful-waiting with supportive care in children with OSAS. They included 464 children (5–9 y) with OSAS (AHI > 2 events/hour). Extremely obese children, children with recurrent tonsillitis and children with attention deficit – hyperactivity disorder were excluded. The normalization of PSG measurements occurred in 79% of the early-AT group and 46% of the watchful-waiting group. Thereby, compared with watchful waiting, early-AT improved the behavior and quality of life. However, there was no significantly improvement of attention or executive function [87]. Certain subgroups have much lower success rates after AT. A meta-analysis of 110 obese children showed that 49% had a postoperative AHI <5 events/h, 25% AHI <2 events/h, and 12% AHI <1 events/hour [14]. AT is also less successful as treatment children with DS. Marcus et al. studied 49 children and four adults with DS (mean age 7.4 y). Of the eight children who underwent an AT, complete normalization was only in three subjects and the study did not provide details regarding the age, pre- and post-operative AHI of the AT group [18]. A retrospective study investigated 21 children with OSAS and DS with 76% of patients having an abnormal AHI before surgery. After TA, 48% continued to have an elevated AHI. If hypercarbia and hypoxemia were included in the result analysis, 67% continued to have abnormal PSGs after surgery [88]. Another retrospective study compared the outcomes of AT in 11 DS children (mean age 8.5 y) and nine non-DS children (mean age 6.5 y). Both groups were overweight. Although a significant improvement was observed in the DS children with a decrease in AHI from 15.3 ± 12.6 events/h to 9.14 ± 10.5 events/hour ($p = 0.04$), 82% had a postoperative AHI > 2 events/h. In the non-DS group 45% had a postoperative AHI > 2 events/h [89]. Rosen et al. did an anonymous Internet based questionnaire with parents of DS children. It was found that 83 out of 250 had undergone AT, 47.5% continued to have witnessed apnea and 28.9% continued to gasp or choke during sleep more than once a month [90]. This is most likely due to the incomplete treatment of multilevel obstruction by AT [91]. The choice of surgical tools and techniques certainly affects the success rate, but the individual patient's anatomy most likely plays an important role as well. Imaging may assist in selecting the most appropriate treatment. We will now discuss the different imaging methods with regards to their value in predicting the effect of treatment with a focus on adenotonsillectomy [9,86,92–94].

Lateral neck radiography

No studies have described whether lateral neck radiography can predict the effect of treatment. The study by Jain et al. investigated 40 children who underwent adenoidectomy and/or tonsillectomy. Lateral X-rays were obtained from all patients. This study found a significant reduction in the desaturation index scores following

surgery in the obstructive group. The study did not investigate whether radiography could help to predict the effect of the treatment [28].

Cephalometry

No studies have used cephalometry to predict the effect of AT in a pediatric population.

MRI

Nandalike et al. investigated 27 obese children with OSAS that had a mean age of 13 y. All underwent PSG and MRI during wakefulness before and after AT. The volumetric analysis showed an increase in nasopharyngeal and oropharyngeal airway volumes post-AT, but no significant reduction in adenoid volume. The volume of the palatine tonsils decreased significantly in 88% of the children. AT was associated with a significant increase in soft palate volume, tongue size and head and neck subcutaneous fat tissue. A complete resolution of OSAS only occurred in 44% of cases and complete resolution was achieved in only 22% of children with severe OSAS. Residual OSAS was associated with substantial residual adenoid tissue, an increase in volume of the soft palate and to a lesser extent, an increase in volume of the tongue [95]. Guimaraes et al. investigated 71 obese children with sagittal fast spin-echo inversion recovery imaging. They concluded that obese children had a high frequency of enlargement of the lingual tonsils with a significantly higher prevalence in those who had previously undergone tonsillectomy. Enlarged lingual tonsils may play a role in the pathogenesis of obstructive sleep apnea in obese children [96]. The aim of the study of Fricke et al. was to compare lingual tonsil size between children with OSAS (including a subanalysis in children with and without DS) and a group of normal controls by cine MRI. Children with persistent OSAS despite AT showed an increased prevalence of lingual tonsil hypertrophy, specifically, 33% of subjects with persistent OSAS compared to 0% of control subjects. This frequency was specifically increased in children with DS and persistent OSAS, with 50% presenting with measurable lingual tonsils compared to 22% of children without DS [44]. Donnelly et al. concluded that persistent OSAS in DS has multiple causes. The most common causes include macroglossia, glossoptosis, recurrent enlargement of the adenoids and enlarged lingual tonsils [97]. Shott et al. investigated 15 patients with OSAS by cine MRI. All patients had previously undergone AT. Recurrent adenoid tissue, glossoptosis, soft palate collapse, hypopharyngeal collapse and enlarged lingual tonsils were identified as causes for residual OSAS [91]. As mentioned earlier, the study by Cappabianca et al. showed that OSAS is a combination of varying degrees of obstruction in three different compartments, the air lumen, soft tissues and facial skeleton. Accordingly, Cappabianca et al. suggested that the cumulative effect of the abnormalities found in the different three compartments greatly impact the choice for the most appropriate surgery leukotriene receptor antagonist [65].

CT

Preliminary data of the study by Van Holsbeke et al. showed that differences in the UA could be identified in subjects who did not benefit from local treatment. Post-treatment data were available for 15 patients diagnosed with OSAS. Specifically, eight patients underwent adenotonsillectomy, two patients adenoidectomy and five patients were treated with leukotriene receptor antagonist. A control PSG showed residual OSAS in four out of 15 patients. None of the patients with residual OSAS had their smallest cross-sectional area located in the overlap regions, and this frequency was significantly lower than in their peers with normal sleep (64%). There were no other differences between these two groups [71]. There have been no studies that have investigated the CBCT findings of the upper airway and treatment outcome in children.

Functional imaging

Mihaescu et al. described a case report of a 15-y-old morbidly obese patient who underwent MRI before and after AT. 3-D airway models were constructed and CFD was applied. They concluded that the resolution of OSAS after treatment in this patient was associated with changes in flow characteristics. Specifically, AT resulted in decreased pressure differentials across the airway walls and thus lower compressive forces that can predispose to airway collapse [98].

Conclusions

No studies have investigated whether lateral neck radiography or cephalometry can predict treatment response. On the other hand, one CT and several MRI studies have described reasons for residual OSAS after AT based on images obtained after the actual surgery. There have been no studies on using imaging methods before surgery to guide treatment selection. CFD has also not been used in this setting. In conclusion, even in otherwise healthy children with OSAS, AT does not have 100% efficacy. To avoid unnecessary risks and ineffective surgeries, the indication for surgery should be correctly set. Therefore, it seems crucial to couple the exact individual anatomical risk factor with the most appropriate treatment. Imaging could be a non-invasive tool that could assist in selection of treatment, but more studies are required to validate its utility.

Practice points

1) Lateral neck X-ray is a simple technique and has relatively good predictive values for the diagnosis of OSAS. The value can be improved by incorporating certain clinical predictors.
2) A cephalometric radiograph is a standardized X-ray with fixed object source distance. It remains unclear if it can be a diagnostic tool, because the discussed studies have not reported its sensitivity or specificity. However, if a radiograph revealed craniofacial anomalies, a referral to an orthodontist will be required.
3) Several studies used MRI or CT and showed detailed correlations with OSAS severity or identification of critical anatomical sites. However, no data on their sensitivity or specificity have been published.
4) CFD involves information on the functional and anatomical properties of the UA, such as resistances and flow characteristics, based on MRI or CT images. Limited studies have used this technique, but there exists a correlation with CFD parameters and OSAS severity. This technique may give more insight into the pathophysiology of OSAS in a non-invasive manner.
5) Obstructive sleep apnea is associated with a number of significant complications and it should therefore be correctly treated. The efficacy of (adeno) tonsillectomy is not 100%.
6) Children with other predisposing factors have much lower success rates and more often require other complex surgeries. Accordingly, they are at increased risk for surgery-related complications. Imaging could be a non-invasive tool that could assist in this treatment but more studies are needed to validate its utility.

Research agenda

In the future, more studies on the following are warranted:

1) To investigate the value of CFD as diagnostic tool, that is, using imaging before the AT.
2) To investigate the different techniques that can assist in the treatment in subgroups, including children suffering from obesity, Down syndrome or other craniofacial anomalies.

Conflict of interest

The authors have no conflict of interest to declare.

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